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Technical Report ONR-70-1, June 1970

Research supported by:

Office of Naval Research
Contract N 00014-67-A-0305-0014
Work Unit NR 196-092

WHAT MOVES, THE AIRPLANE OR THE WORLD?

A Review of the Motion Relationship Problem in Presenting Aircraft Attitude and Guidance Information

Prepared by:

Steven L. Johnson and Stanley N. Roscoe

For:

Engineering Psychology Programs
Office of Naval Research
Department of the Navy

AVIATION RESEARCH LABORATORY
Institute of Aviation
University of Illinois-Willard Airport
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FOREWORD

This report is a review of the background for a research program currently being conducted at the Aviation Research Laboratory of the Institute of Aviation, University of Illinois, supported by Engineering Psychology Programs, Office of Naval Research, Washington, D. C. The investigation is concerned with the effects of display motion relationships upon airplane pilot performance on complex tasks involving the control of flight attitude in response to dynamic steering commands. Under specific evaluation is the applicability of the frequency separated presentation of control inputs, aircraft responses, and steering commands. Dependent variables include the speed with which relatively inexperienced pilots master instrument flight tasks and the ease with which highly experienced instrument pilots transition to new display configurations.

ACKNOWLEDGMENTS

The program under which this report was prepared was initiated by Dr. James W. Miller, former Director of Engineering Psychology Programs, Office of Naval Research. Dr. Marshall J. Farr, former Assistant Director of Engineering Psychology Programs, was the technical monitor during the initial phase of the project. Technical guidance and encouragement to expand the scope of the program were rendered by Dr. Martin Tolcott, who succeeded Dr. Miller as Director of Engineering Psychology Programs, and Gerald S. Malecki, who succeeded Dr. Farr as Assistant Director. Assistance has also been rendered by James P. Cathey, Office of Naval Research Resident Representative at the University of Illinois, and Dr. Morton A. Bertin, Coordinator for Psychological Sciences, Office of Naval Research, Chicago, Illinois.

Dr. Charles R. Kelley, who held a George A. Miller Visiting Professorship at the University of Illinois during the spring of 1970, and Dr. Robert C. Williges, Assistant Head of the Aviation Research Laboratory, have contributed to the content and organization of the material presented. William H. Schmidt of the Scientific Writing Staff of the Aviation Research Laboratory edited the report.

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INTRODUCTION

In 1968, 76 fatalities occurred in 89 airplane crashes classified as weather disorientation accidents. Of these 89, a substantial number occurred when an airplane with a normally operating gyro horizon display was flown into the ground in a tight spiral.

Entry into a high-speed spiral dive is temporally associated with entry into a cloud and the shift in visual frame of reference necessitated by loss of visual contact with the ground. Planes flown into a cloud by pilots without specific training in techniques for making 180-degree level turns by reference to cockpit instruments will be in a well-developed graveyard spiral within an average of 178 seconds (Bryan, Stonecipher, and Aron, 1954).

The fact that pilots frequently misread or misinterpret aircraft flight displays has plagued researchers throughout the history of aviation. The bulk of evidence regarding pilot errors is found in sources other than formal experiments. Aircraft accident reports and accounts of near-accidents offer much information related to this problem.

One of the first investigations which considered the problem of pilot errors quantitatively was conducted by Fitts and Jones (1947a). This report collected and analyzed accounts of 420 errors made by pilots while operating aircraft controls. The statistics obtained from this study revealed that the design of aircraft equipment must take into account the capabilities and limitations of the human operator.

In the same year, Fitts and Jones (1947b) investigated 270 errors made by pilots with respect to reading and interpreting instruments. Data were obtained through interviews and written reports. The reported errors were classified into nine categories:

1. Errors in interpreting multirevolution instrument indications
2. Reversal errors
3. Signal interpretation errors

4. Legibility errors
5. Substitution errors
6. Use of an instrument that is inoperative
7. Scale interpretation errors
8. Errors due to illusions
9. Forgetting errors

The artificial horizon, or attitude indicator, was shown to contribute to two of these error categories, reversal errors and errors due to illusions.

Reversal errors are the result of misinterpreting an instrument indication and making a control movement that aggravates rather than corrects an undesirable condition. With respect to the attitude indicator, there were 19 (out of 270) reversals in interpretation of the angle of bank shown on the display. A typical statement made by a pilot was found to be:

> I glanced away from the instruments while making a steep bank in a C-47. Upon glancing back at the artificial horizon, I was confused as to the direction of turn shown by the little pointer which indicates degree of bank. Upon beginning to roll out, I used exactly opposite aileron control from what I should and thereby increased the bank to such an extent that it was almost 90° and considerably dangerous (Fitts and Jones, 1947b, p. 19).

Reversal errors were also found to be associated with the angle of pitch shown by the display.

The other category in which a number of errors was attributable to the attitude indicator was that of errors due to illusions. It was found that 14 errors were due to misconceptions of attitude which arose because of a conflict between body sensations and instrument indications. These errors were particularly prevalent during instrument or marginal weather conditions.

The findings of these studies illustrate that pilots do make a number of errors on aircraft attitude displays. The problem is that, although this number is relatively small, the consequences of these errors are often tragic, and the amount of over-learning associated with the use of this display dictates that the number should be closer to zero.

Fitts and Jones (1947b, p. 22) felt that because the reversal of instrument sensing occurred so frequently, it was worthwhile to consider in detail some of the causes of such errors. They state, "The proper directions of motion of flight instruments for maximum ease of sensing has been under discussion since instrument flying was inaugurated . . . . However, after twenty years, the results of the present investigation indicate clearly that the problem has not been solved satisfactorily . . . . " With respect to attitude indicators, more than two decades have passed since the studies by Fitts and Jones; and although the great majority of the experimental evidence indicates the inadequacies of the conventional artificial horizon display, it is still the one commonly in use. Therefore, the fundamental problem has not been solved.

In the display of aircraft attitude, either of two basic movement relationships may be employed. In one case, aircraft coordinates are used as the reference system (moving outside world); in the other case, earth coordinates are used (moving aircraft).

These basic forms of presentation apply to any spatial information, including position and altitude as well as attitude. They are described in the literature under many different names. In some cases, the same terms are used in the opposite sense. For example, the term earth referenced (as opposed to aircraft referenced) has been used by certain authors and many pilots to refer to displays in which the movement of the display elements is presented in aircraft rather than earth coordinates. Evidently this usage derived from the notion that moving compass cards and artificial horizon bars maintain spatial alignment with their real-world counterparts and are, therefore, earth referenced.

One of the functions of this report is to order the closely related and frequently interchanged terms into a standardized vocabulary. The two basic coordinate systems in which spatial flight information may be displayed are earth coordinates and aircraft coordinates. Earth Coordinates refers to three orthogonal axes fixed in position relative to terrestrial space (as opposed to inertial or celestial space). One axis is vertical and eminates from the center of the earth; the second is orthogonal to the first and is oriented relative to the north pole; the third is orthogonal to the

first and second. Aircraft Coordinates refers to he longitudinal, lateral, and vertical (x, y, and z) axes of the aircraft. The listings given below relate various terms commonly used in referring to aircraft displays to the corresponding coordinate system:

Display Presented in Earth Coordinates		Display Presented in Aircraft Coordinates
Outside-in		Inside-out
Fly-from		Fly-to
Moving airplane		Moving horizon
Moving pointer		Moving card or tape
Aircraft referenced or stabilized	(some authors)	Earth referenced or stabilized
Space stabilized	(other authors)	Aircraft stabilized

This report deals with three aspects of display motion relationships. First, display variables are identified, and research contributing to the knowledge we now have concerning these variables is reviewed. This research involves, to a large extent, the pilot's frame of reference particularly with respect to figure and ground relationships. The problem of what the pilot considers as moving, the aircraft or the outside world, under different conditions, and the possible explanations for the preferences in motion relationships are investigated. The findings of experiments associated with the moving horizon versus moving airplane controversy in aircraft attitude presentation are discussed in chronological order where appropriate. Display motion relationships are considered as they pertain to pursuit as opposed to compensatory tracking. The final discussion in the section considers the possible application of the combination of earth and aircraft coordinates in the same display.

Next, the research problems encountered in the study of flight displays are considered. These problems include: the pilot's experience level, the environment in which the research is conducted, with special attention given pilot-confidence considerations, the task variables associated with an evaluation

of a display configuration, and the performance measures appropriate to evaluation.

Finally, requirements for future research on aircraft attitude displays are summarized. The display variables that need systematic investigation are discussed in terms of the research problems associated with those variables.

DISPLAY VARIABLES

What Should Move?

In attempting to determine the preferred motion relationships among display symbols and their real-world counterparts, it is necessary to consider the question of whether the pilot thinks that the display represents his vehicle as moving against the external world or that the display represents the external world as moving about his vehicle. This question involves what has been termed the pilot's frame of reference. With respect to the presentation of aircraft attitude, the issue is illustrated graphically in Figure 1. In whatever manner attitude information is displayed, it is necessary for the pilot to think that his aircrafr is moving. If he thinks that the outside world is moving, he is disoriented and subject to vertigo.

From the date of the invention of gyroscopic flight instruments, including turn indicators, directional gyros, and attitude gyros, the frame of reference for display presentation has been a subject of controversy. The argument found its way into the literature early and was stimulated greatly by the fog flying exploits of Lieutenant James Doolittle under the sponsorship of the Daniel Guggenheim Fund (1930). On September 24, 1929, Doolittle proved conclusively that it was possible to take off and land an airplane by instruments alone. Doolittle took off with the cockpit of the airplane completely covered, flew a distance of 20 miles, and landed at almost exactly the same spot from which he had taken off. The attitude indicator used by Doolittle was the Sperry Horizon which was the prototype for the conventional artificial horizon presentation.

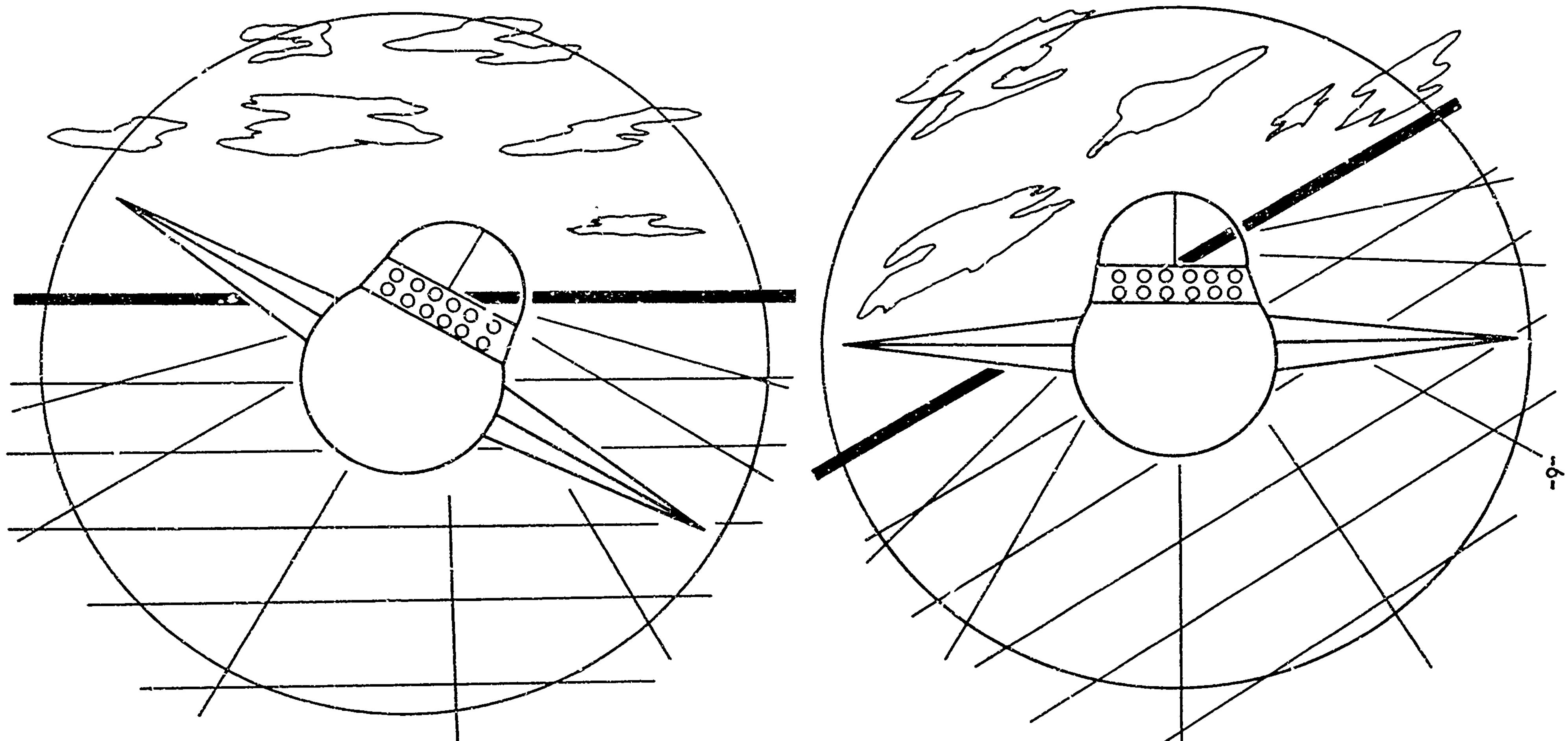

FIGURE 1

Illustration of the basic figure-ground controversy in the presentation of aircraft attitude: a question of point-of-view.

Lieut. Commander John R. Poppen (1936), a naval flight surgeon, presented a rationale for the motion relationship of the Sperry Horizon used by Doolittle. Poppen stated that the correct form of presentation was an exact analog of what would be viewed through the windscreen in contact flight. Essentially he considered the display to be a porthole through which the pilot views a symbolic analog of the real horizon. Poppen carried this line of reasoning to the point of advocating a displacement of the gyroscopic turn needle to the left while in a right turn so as to keep the display index in proper perspective (perpendicular) to the external world. This same rationale has prevailed through the years in support of the moving horizon attitude presentation. Nevertheless, the problem of frequent interpretation and control errors associated with this display remains.

Figure and Ground

The problem of pilot errors on moving horizon attitude displays may be explained in the context of the psychological phenomenon of figure and ground. Psychologically, an object is perceived as moving in relation to other objects in a visual field. The part of the field of view that appears to be stationary is customarily called the background or simply the ground, and the object that is moving is called the figure. When the entire visual field is moving in relation to the observer's eye, as occurs with head movement, the observer usually perceives that he himself is moving and that the background is stationary. The question then becomes, do the figure and ground relationships between the aircraft and the outside world change when the pilot shifts his attention from the outside world to his attitude indicator on the panel inside the cockpit?

Rubin (1915, 1921) who first brought out the psychological importance of figure and ground distinction, classified the phenomenal differences between figure and ground as follows: ". . . (1) the figure has form, the ground is relatively formless, or if the ground has form it is due to some other figuration upon it and not the contour separating it from the figure; (2) the ground seems to extend continuously behind the figure and not be interrupted by the figure;

(3) thus the figure has some of the character of a thing, whereas the ground appears like unformed material; (4) the figure tends to appear in front, the ground behind; (5) the figure is more impressive, better remembered and more apt to suggest meaning." (Rubin's ideas were extracted from a secondary source: Woodworth, 1938, p. 630.)

Grether (1947) postulated a cause of reversals in interpreting flight displays in terms of the concepts of figure and ground. He states:

> The actual horizon is normally accepted by the pilot as a fixed or stable frame of reference. It becomes a ground (or background) against which his and other aircraft are moving figures. When the horizon disappears, as in instrument flying, the pilot apparently shifts to the cockpit of his own aircraft as the stable reference or ground against which all moving pointers, including the gyro horizon bar, are reacted to as figures. The small, narrow and fallible moving bar apparently cannot substitute for the distant, massive, and infallible true horizon as a stable frame of reference for the pilot. By reacting to the gyro horizon bar as figure instead of ground, he is led to an exactly reversed interpretation (pp. 11-12).

If the pilot's frame of reference changes when he views a small, abstract instrument representation of the outside world, as opposed to the outside world itself, this change must involve a shift in the figure-ground relationship. Specifically, the aircraft's instrument panel or even the framed aperture of an individual display becomes the background against which the display elements move.

The possibility that varying the size of an attitude display can cause a change in the pilot's frame of reference was investigated by Kelley, DeGroot, and Bowen (1961). They were unable to elicit a reversal of the subject's perceived figure-ground relationship with displays subtending visual angles ranging up to 67 degrees. In all cases the moving element of the display was perceived as the figure.

The opposite figure-ground relationship prevails when a display presents a dynamic literal image of the outside world as in the case of a projection periscope

(Roscoe, 1948 and 1951; Roscoe, Hasler, and Dougherty, 1966). With display screens subtending visual angles ranging from 30 degrees down to 7.5 degrees (a two-inch screen viewed from 15 inches) and presenting a forward-looking view as narrow as 3.75 degrees (2X magnification on the two-inch screen), no control reversal was observed during more than 135 hours of formal and informal flight experimentation involving more than 25 different pilots of widely varying experience. This finding, contrasted with that of Kelley, DeGroot, and Bowen, strongly suggests that the dynamic properties of a highly resolved literal image in natural color, as opposed to an abstract symbolic representation of the outside world, have a more compelling effect on the perceived figure-ground relationship than does the size of the visual angle subtended.

Control-Display Relations

Motion compatability must be considered in conjunction with the pilot's frame of reference. Depending on whether the desired or the actual position of a pilot's aircraft is the frame of reference, the display element may move either in the same direction as or in a direction opposite to the control input. That is, the operator may consider the movement of a display symbol from the fixed reference either as something he must follow to correct his error or as something he has control over and must bring back to the fixed reference. In the first case, a displacement of the symbol to the right of the center reference point would dictate a right control movement; in the second case, it would call for the opposite response.

When a moving element of a display represents some aspect of the performance of the vehicle over which the pilot has control, as in the case of a vertical speed needle, the display is said to require a fly-from response. When the needle is below its desired position, the proper response is to fly up, or "away from," the needle. Conversely, when the moving element represents an index of desired performance, as in the case of a course deviation needle, the display requires a fly-to response. If the needle is to the right of center, indicating that the airplane

is to the left of course, the proper response is to fly right, or to the needle. With fly-to displays, control and display movements are in opposite directions; with fly-from displays, they are in the same direction.

An experiment which studied motion relationships in the context of cross-pointer type displays was done by Gardner (1950) in a C-3 Link trainer. He compared the fly-to type of presentation, in which a fixed point (usually the center of the display) represented the aircraft's actual position and the moving symbol represented the desired position, to the fly-from type, in which the relationship was reversed. The performance measure used in this study was the percent of time the subject held the vertical and horizontal needles within certain tolerances. The subjects were pre-flight cadets who had no flight experience.

Gardner's study showed a significant superiority of the fly-from motion relationship with respect to the vertical needle pointer; however, the motion relationship was not critical with respect to the horizontal needle pointer. The latter observation might be explained to some extent by the findings of Warrick (1947). He investigated control-display motion relationships with respect to circular dials and rotary control knobs. No stereotyped preference was found when the display and the control motions were in different planes.

Moving Airplane versus Moving Horizon

With respect to attitude presentation specifically, the central question is whether the aircraft symbol or the artificial horizon symbol moves with reference to the fixed display coordinates. Despite the extensive experimental evidence favoring the moving airplane presentation, the issue is not settled after nearly half a century of controversy. The validity of results from ground-based simulator experiments has not been established for questions in which physical acceleration cues are believed to be important, and the results of flight experiments are inconclusive.

One of the first experiments on aircraft attitude presentation was by Browne (1945), who compared two attitude indicators using a Link trainer. One was a

conventional British instrument in which a symbol representing the aircraft was stationary in the center of the display and an artificial horizon bar moved in the customary fashion. The other display was an experimental instrument which had artificial horizon bar segments fixed across the face of the display and a two-dimensional aircraft symbol that moved in relation to it to show bank angle. The experimental display proved superior to the conventional moving horizon display. Browne believed that the problem with the conventional display was that the pilot was identifying himself with the moving element of the display rather than identifying the moving element with the real horizon.

Later in the same year Loucks (1945) did an expanded follow-up study on Browne's experiment. Loucks compared four types of experimental attitude indicators with the conventional instrument using naive subjects. The four experimental displays differed respectively from the conventional display as follows: (1) bank scale marks were removed, (2) the bank scale rotated with the horizon line, (3) the bank scale was positioned below the horizon line, and (4) the rotation of the horizon line was reversed from that in conventional displays.

The display using the reversed rotation of the horizon line proved to be substantially superior to the conventional attitude indicator. This experimental display was superior with respect to pilot performance and was preferred. Loucks concluded:

> . . . the superiority of the reversed rotation type of artificial horizon has been exhibited in spite of the fact that when the aircraft assumes a right-roll attitude, the indicator registers this maneuver by showing the miniature airplane with its left wing dipped below the horizon bar. . . .it would appear that the direction of rotation of the moving elements in the instrument comprises the factor which the novice reacts to most immediately --a factor which the more experienced pilot has learned to disregard. . . .if the correct static pattern were presented along with the appropriate dynamic relationship of the moving elements, e. g., when the horizon remains fixed and the miniature plane rotates, the resulting instrument might be superior to the reversed rotation horizon. . .(quotation taken from reissue of original paper in Fitts, 1947, p. 129).

In 1952 Browne carried out an experiment to study the figure-ground relationship of the attitude indicator which he suggested as the cause of the results of his 1945 study. A standard British instrument flying trainer was used. The subjects were experienced pilots and pre-flight cadets with no experience in using attitude display indicators.

Once again, for novice pilots the moving aircraft display exhibited a definite superiority over the moving horizon display with respect to errors made in the control of bank but not with respect to errors in pitch. This result might also be explained by Warrick's (1947) finding that no clear-cut control-display motion stereotype existed when the control and display were in different planes. The non-pilots preferred the new display to the old one by a six-to-one margin. The results involving the experienced pilots revealed that, although they preferred the moving aircraft display, the difference in their performances on the two displays was not significant.

An interesting aspect of Browne's study was that, when subjects first tested on one display were switched to the other, the positive transfer from the moving horizon to the moving aircraft was four times as great as the transfer in the opposite direction. Browne (1952) explains this by stating, "This is to be expected if the new display (A) [moving aircraft] is easier to read than the old. . . " (p. 6).

A series of studies was done at Hughes Aircraft Company between 1953 and 1960. These studies were concerned with pilot steering performance in radar-directed interceptor attacks. Figure 2 depicts the various display configurations employed in different studies of this series.

The first of these studies was done by Nygaard and Roscoe (1953). Three experimental displays were compared with the conventional moving horizon display in an interceptor attack simulator. The moving horizon display configuration consisted of a shrinking time-to-firing circle, a smaller reference circle, a two-segment bar representing the horizon, and a steering error dot all generated on a standard CRT. An overlay with etched markings that

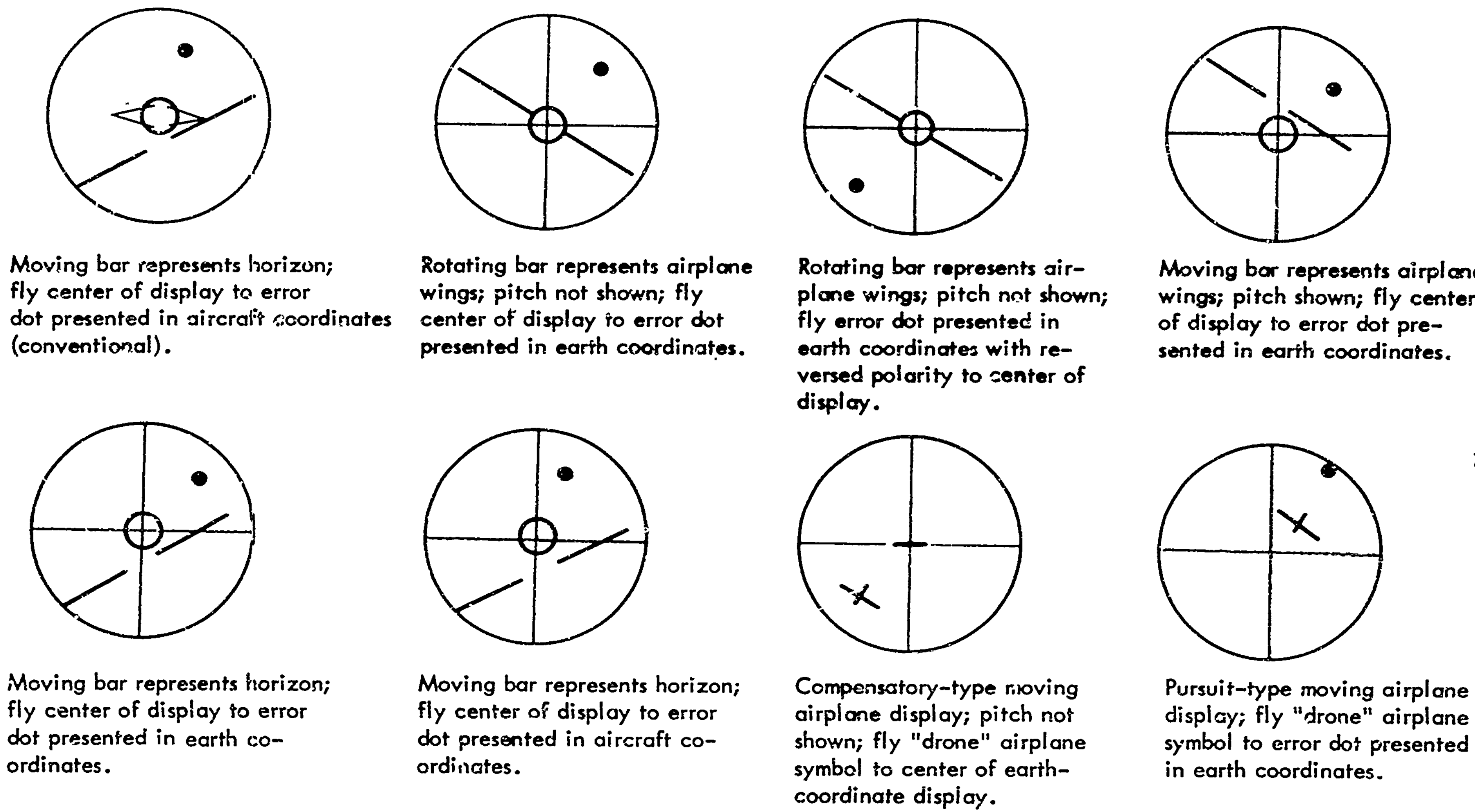

FIGURE 2. Various radar attack display configurations studied at Hughes Aircraft Company.

In all cases illustrated, horizontal and vertical angles-to-turn-through and bank and pitch (if shown) represent comparable flight geometries.

represented the aircraft's wings was placed over the CRT display. The horizon bar rotated and translated in the conventional manner to show roll and pitch respectively. The angular steering error was zero when the steering dot was in the center of the reference circle.

In the first of the experimental displays the conventional attitude presentation was reversed so that what had been the segmented horizon bar now represented the wings of the aircraft. The second experimental display differed from the first only in that no pitch information was presented. The third experimental display differed from the second only in that the polarity of the steering error indication was reversed in both azimuth and elevation so that it required the pilot to fly the dot to the reference circle rather than the circle to the dot.

The subjects were 48 pilots with varying numbers of flying hours and types of flying experience. None of the subjects had flown a radar attack display prior to the experiment. The azimuth and elevation miss-at-firing angles were used as indices of performance.

A comparison of the learning curves for pilots using the various displays showed performance with each of the experimental displays to be significantly superior to that with the moving horizon display. The results of a series of post-test transfer trials showed that the moving horizon display group had little difficulty in transferring to the second experimental display which had reversed bank movement and showed no pitch information. The pilots who began on any of the experiemental displays and transitioned to the moving horizon display encountered greater difficulty.

Another preliminary comparison made in this study was between the second experimental display of the first comparison (airplane moved with no pitch shown) and a fourth experimental display. This display had the bank attitude of the aircraft and the steering error both shown by a single moving symbol designed to represent an airplane as viewed from the rear. The task was to fly the "drone" airplane symbol to a reference bar (target) fixed in the center of the display.

The results showed that there was little difference in the final levels of performance for the groups using the two displays. However, during early trials, use of the drone airplane display resulted in superior steering performance in azimuth.

The second Hughes study, by Roscoe, Wilson, and Deming (1954), determined the effects upon the performances of experienced pilots when transferring from the conventional moving horizon display to the drone-type experimental moving airplane display described above. The airplane symbol moved vertically in relation to the horizon bar to indicate vertical steering error and laterally to indicate horizontal steering error. The tilt of the airplane symbol from the horizontal indicated the aircraft's bank attitude. This display was the same experimental drone airplane display used in the previous study.

The subjects were ten Hughes test pilots. Unlike the subjects in the previous experiment, all of these pilots were experienced in flying radar-directed attacks using the moving horizon display. The subjects performed in seven different sessions of 30 trials each in the attack simulator on seven different days. In the first three sessions, the moving horizon display was used. The moving airplane display was used for the next three sessions, and the moving horizon display was used again on the seventh. A miss-at-firing value was obtained on each trial for both azimuth and elevation, and those values were used as error scores.

The results showed that the amount of variable azimuth and elevation steering error for the moving horizon display tended to decrease until the middle of the second session. From this point, the steering errors reached an asymptotic level. The statistical analysis showed that the overall levels of performance for both the third series using the moving horizon display and the initial series using the moving airplane display were not significantly different. Performances for the third series of trials with the moving airplane display were significantly better in both azimuth and elevation than performances for the third series using the

moving horizon display. This result indicates that the terminal level of performance is superior for the moving airplane display, at least in the simulator. A disadvantage of this study was that a control group was not run to find out the effect of learning the task over the seven sessions. Although the seventh session was of a counter-balancing nature, it was not of sufficient length to establish the pilots' terminal performance when transferred back to the moving horizon display.

The third Hughes study, by Roscoe, Hopkins, and McCurley (1955), was a flight experiment conducted in an F-86D aircraft with an E-4 radar fire control system. The steering performance of experienced interceptor pilots with the conventional moving horizon display was measured during an initial series of approximately 12 attacks by each of six pilots. The pilots then transferred to the moving airplane display and performed two series of 12 attacks each, followed by a post-test series of 12 attacks on the conventional display.

The results obtained did not reflect the pronounced superiority of the moving airplane display observed in previous simulator studies. However, terminal performance using the experimental display was not reached, and the study served only to indicate the limited extent of difficulty that skilled interceptor pilots might encounter during their initial transition to the new display. After a transient increase in steering error when first transferring from the moving horizon to the moving airplane display, the pilots quickly adjusted to the new control-display relationships. On their second series with each display, group performances did not differ significantly.

Gardner (1954) conducted an experiment comparing five attitude indicators having different movement relationships: (1) a conventional moving horizon display, (2) a three-dimensional, moving aircraft display, (3) a stabilized sphere display, (4) a reversed pitch, stabilized sphere display, and (5) a British presentation which

used one moving aircraft instrument to show bank and a second moving aircraft instrument to show pitch. The displays were static in that the experimenter set their position from the back of the instrument.

The study was divided into two parts, one using a manual response and the other a verbal response. The subjects were 50 experienced instrument pilots and 50 non-pilots. The task in the manual response tests was to move a control stick in the proper direction to correct the deviation from straight-and-level shown on the display. The task was the same for the verbal response tests except that the subjects simply told the experimenter what the correct control movements would be. The performance measures were the number of correct movements and the latency of the control movement or verbal response. The tests were carried out in a static C-3 Link trainer.

This study revealed no significant differences among the displays in the number of reversal errors made. With respect to response times, the moving aircraft display had significantly shorter manual and verbal response times for novices; however, no differences were found for the experienced pilots. The only other significant results were that the British display was superior to the moving horizon display only in verbal response time and that the stabilized sphere display was inferior to the rest of the displays, even the reversed pitch stabilized sphere. These results, although slightly favoring the moving aircraft displays tested, provide no conclusive evidence concerning either the superiority or inferiority of the moving aircraft display principle.

In 1955, investigators at Dunlap and Associates conducted a study on attitude display motion relationships to determine whether ex-pilots could adapt to the moving aircraft type of display more quickly than they could re-adapt to the one they had previously used. The subjects had an average interval of 5.8 years since their last flights. The subjects also had averages of 2556 flight hours and 300 hours of instrument time. The tests were carried out in a fixed-base C-11B jet

simulator which had control responses approximating those of an F-80 aircraft. The pilots were given a number of different maneuvers to fly which varied in complexity. In the last phase of the experiment, the task required the pilots to recover from unusual attitudes.

The number of reversals on the moving horizon display was 3.6 times the number on the moving aircraft display. The number of reversals made was also shown to be a function of the order of presentation. The group that used the moving aircraft display first made 15 reversals on it as opposed to 81 on the moving horizon display. A second group, for which the order of presentation was reversed, had 23 reversals on the moving aircraft display as opposed to 55 on the moving horizon display. The moving aircraft display also proved to be significantly superior in the amount of time the pilots needed for recovery from the unusual attitudes.

These results are particularly interesting in that the subjects found it easier to adapt to the new moving aircraft display configuration than to re-adapt to the moving horizon display with which they had spent many previous flying hours. The investigators attributed this fact to the idea that, of the two displays, the moving aircraft display is the, ". . .'more natural'. . ." (Dunlap and Associates, 1955, p. 20).

Weisz, Elkind, Pierstorff, and Sprague (1960) investigated various forms of radar steering display designs. They compared five attitude indicators, four experimental moving aircraft displays, and one conventional moving horizon display. Three of the experimental displays presented rate information, such as azimuth and elevation angle rate, along with the standard information presented on attitude indicators. The fourth experimental display presented the same information as the conventional moving horizon display but with different motion relationships.

The subjects were operational military pilots, some of whom had radar fire control experience flying the conventional moving horizon configuration. For four of the displays, the task was to fly the center of the displays to the error dot.

For the fifth display, the task was to fly the moving aircraft symbol to the center of the display. The tests were carried out in a moving-base flight simulator. All four experimental displays resulted in greater mean time on target scores than the conventional display. The experimental display having the same information as the conventional display was superior by a very small margin, although still significantly superior.

Some evidence has been found that under certain experimental conditions, the moving aircraft presentation was not superior to the moving horizon presentation, and in one study the moving horizon display was reported to be superior.

In the first of two studies, the later of which was discussed previously, Gardner and Lacey (1954) compared five different motion relationships in attitude indicators. The five instruments used were: (1) a conventional moving horizon display, (2) an experimental moving aircraft display, (3) a sphere stabilized with respect to the earth's surface, (4) a reversed pitch stabilized sphere, the same as (3) except that the pitch indication was reversed, and (5) a semi-three-dimensional moving aircraft display in which a cross section of an aircraft's wing moved behind a pivoted cross section of the tail.

The subjects were Air Force pilots with minimums of 1500 hours of flying time and 150 hours of instrument time. The tasks were to hold the aircraft level and to make turns using 21 degrees of bank while the experimenter introduced turbulence. The tests were carried out in a modified C-8 Link trainer.

The results were quite different from the studies previously discussed. The number of control reversals was significantly greater for the moving aircraft than for both the conventional moving horizon and the three-dimensional moving horizon displays when periodic gusts were administered during straight-and-level flight. There was no significant difference between any other display and the conventional display. Gardner and Lacey attributed their results to habit interference due to the extreme amount of time the pilot subjects had flown using the moving horizon type of display.

The same experimenters then carried out a second experiment, described in the same report, in which the moving horizon and moving aircraft displays were compared using naive subjects. The experimental procedure was the same as in their first experiment. The group that used the moving aircraft first had significantly fewer aileron reversals in both straight-and-level flight and 21-degree banked turns; the group that used the moving horizon first encountered no difference. When the scores of the two groups were combined, there was a significantly smaller number of reversals with the moving aircraft display. This study points out the fact that when a comparison of aircraft displays is made, the subject sample is an important factor to be considered.

A study which found differing results as a function of experimental procedure was conducted by Douvillier, Turner, McLean, and Heinle (1960). These investigators compared the moving aircraft and moving horizon display presentations in fixed-base and moving-base simulators as well as in actual flight. The two displays studied were a drone (moving airplane) display and a conventional circle-dot and moving horizon display. In the conventional display, a fixed reference circle, a moving target dot, and a segmented horizon line were presented on the display face. The target dot was displaced from the center of the fixed circle according to the position of the target relative to the attacker. The pilot flew his aircraft in a manner that would keep the target dot at the center of the fixed circle. The horizon line behaved essentially the same as that of a conventional moving horizon display.

In the drone display, the target symbol, a dash, was fixed at the center of the display. The airplane symbol was displaced from the fixed target symbol according to the position and flight path of the attacker relative to the target. The pilot flew his aircraft in such a manner as to keep the airplane symbol superposed on the fixed target symbol. The rotation of the airplane symbol relative to display coordinates indicated the aircraft's bank angle. Pitch was not shown.

Two experimental flight tasks were employed, one the normal lead-collision beam attack of the F-86D/E-4 system, and the other a tail-chase attack in which the attack steering computer was partially disabled to provide a hybrid pursuit steering computation. For the latter case, the target aircraft made a sudden 1.5-G level turn to the right on each trial. The subjects were two pilots, one with a great deal of experience using the conventional radar-attack display, the other with no radar-attack experience on either display. The performance measure was the radial tracking error in inches of displacement of the moving display element from the zero-error position.

The results were inconclusive in that only one subject was employed in each of two widely differing experience categories, and as in the case of the Hughes flight experiment (Roscoe, Hopkins, and McCurley, 1955), the pilots did not receive sufficient practice to approach their terminal performance levels with the experimental display. Although no meaningful test of statistical significance could be performed, it was evident from the recorded data that the pilot-experimenter familiar with the use of the conventional display (the late D. R. Heinle) experienced difficulty in making his initial transition to the moving airplane display, and his subjective reports were unfavorable. The pilot with no prior experience in the task was tested first with the moving airplane display, and his subsequent performance on the conventional display was not markedly different, although he also expressed a strong preference for the conventional display.

In the fixed-base simulator trials, performances on the two displays were quite similar for both pilots. In the two-degree-of-freedom moving-based simulator, both pilots experienced more difficulty with the moving airplane display than with the moving horizon display. The experimenters concluded:

> In flight the drone display offers no improvement in tracking accuracy over the conventional circle-dot display under the essentially static conditions of attacks against a nonmaneuvering target. For pursuit attacks against a maneuvering target the circle-dot display is appreciably superior in both average tracking error and in variability of tracking error (p. 11).

A study conducted at Bell Helicopter Company by Matheny, Dougherty, and Willis (1963) also dealt with the question of attitude display motion relationships in different experimental environments. They compared performance on moving horizon and moving aircraft display presentations under both fixed-base and moving-base simulator conditions. The simulator was capable of movement in six degrees of freedom, three translational and three rotational.

The three displays used in the study presented a geometrical projection of a ground plane represented by grid squares with a sharp horizon line and a clear sky. In the first display, an aircraft symbol moved against a fixed grid plane. The second display had a moving grid plane with the aircraft symbol fixed in the center. The third display was the same as the second, except that no aircraft symbol was presented. The subjects were required to make judgments of the direction of pitch, roll, or both as given by the visual display or by the visual display and cabin motion combined. The subjects responded by calling out the direction of the movement.

The results obtained from the static simulator condition were similar to those found in the other studies reported. The percent of judgments in error for the moving aircraft display was less than for the moving horizon display. When cabin motion was initiated, the two displays did not differ significantly.

Pursuit versus Compensatory Tracking

When the pilot's task is to null an error arising from a discrepancy between his actual position and his desired position, two forms of presentation have traditionally been used: pursuit and compensatory. A pursuit display uses two indices, one representing the pilot's own aircraft and the other representing the target or desired position, both of which move against a common scale or reference system. A compensatory display uses only one moving index with the direction and distance between this moving index and a fixed reference index representing the error.

An early investigation into the question of pursuit versus compensatory tracking was carried out by Poulton (1952). The purpose of his experiment was to contrast a two-pointer (pursuit) display to a one-pointer (compensatory) display in a tracking situation. Task complexity was investigated with respect to the pilot's relative performances using the two different displays. For all levels of task complexity combined,the error with the pursuit display was approximately half that with the compensatory display. An analysis of average error for the compensatory display revealed that, at the highest level of task complexity, the subjects would actually have produced a lower error score by doing nothing rather than attempting to respond. The superiority of the pursuit display became more pronounced as the level of task complexity increased.

Many studies since this early work by Poulton have shown the overall superiority of pursuit tracking over compensatory tracking. It has also been shown, however, that many factors can affect the amount of this superiority.

Chernikoff, Birmingham, and Taylor (1956) studied the effects of aiding on pursuit and compensatory tracking. Four conditions were investigated: (1) compensatory-unaided, (2) compensatory-aided, (3) pursuit-unaided, and (4) pursuit-aided. In the unaided conditions, only changes in the position of the display marker were presented, whereas, in the aided conditions changes in position, velocity, and acceleration of the display marker were presented. The display was a standard CRT with a vertical line (1/4 inch) representing the controlled vehicle. The subjects' task was to null the error displayed by reducing the distance between the symbols. Integrated tracking error was the performance measure used.

The compensatory-unaided display was significantly inferior to the other three forms. No significant difference was found when the pursuit-aided and the compensatory-aided displays were compared. An unexpected result was that the compensatory-aided display was significantly superior to the pursuit-unaided display.

A new approach was taken to the pursuit versus compensatory tracking question by Senders and Cruzen (1952). These investigators studied tracking performance on what they called combined compensatory and pursuit tasks. The display used during the experim nt was a standard CRT. The tracking task was generated by a rotating cam. A proportional network was used which permitted varying proportions of the problem signal to be fed into the two channels of the oscilloscope. In series with one channel was a subject controlled circle generator. The other channel led directly to the oscilloscope amplifier. This arrangement provided a circle under the control of both the subject and the problem generator and a spot that could be moved by the problem generator. Time-on-target was the performance measure used in this study. Five conditions were tested:

1. 0% pursuit (100% compensatory): The circle moved, and the subject tried to return it promptly and correctly to the (stationary) spot, which provided the zero reference point.
2. 25% pursuit (75% compensatory): The ratio of spot movement to circle movement was 1:3. That is, if the spot moved one degree to the left, the circle moved three degrees to the right.
3. 50% pursuit (50% compensatory): The ratio of spot movement to circle movement was 1:1. If the spot moved two degrees to the left, the circle moved two degrees to the right.
4. 75% pursuit (25% compensatory): The ratio of spot to circle movement was 3:1. If the spot moved three degrees to the left, the circle moved one degree to the right.
5. 100% pursuit (0% compensatory): Only the spot moved; the circle remained stationary unless moved by the subject.

These conditions were achieved by dividing the rotating cam output between the target spot and the follower by using a partitioning circuit.

For all subjects, the time-on-target score increased as the task shifted from compensatory to pursuit tracking. There was no significant difference between the 75 percent pursuit and 100 percent pursuit conditions. The largest difference was found to be between the 0 percent pursuit (100 percent compensatory) and 25 percent pursuit. This result could indicate that a good deal might be gained by using a display which has the target spot move slightly yet keeps the scaling advantages of compensatory tracking.

In a fourth study at Hughes Aircraft Company, Bauerschmidt and Roscoe (1960) compared four different displays involving both pursuit and compensatory tracking in a simulated radar-directed attack steering task. The displays were: (1) moving horizon display with a space-stabilized error dot, (2) moving horizon display with aircraft-stabilized error dot, (3) a space-stabilized compensatory moving airplane display, and (4) a space-stabilized pursuit moving airplane display. With a space-stabilized steering error indication, the error dot moves only in response to changes in the aircraft's flight path or position and not in response to changes in attitude. With an aircraft-stabilized steering error indication, the error dot's position revolves about the center of the display in direct response to changes in the aircraft's bank attitude. With the first two displays the pilot's task was to fly the fixed reference circle to the moving error dot. With the third display, the moving aircraft symbol was flown to a short fixed reference bar at the center; no pitch information was provided. With the fourth display, the moving aircraft symbol was flown to the moving error dot.

The subjects were pilots who had no experience flying radar attack displays. The range of flying time varied from 50 to 5000 hours. The performance measures used were the angle-to-turn-through at firing in degrees for both azimuth and elevation. Although learning was evident for pilots using all four displays, initial performances with either of the moving aircraft displays were superior to terminal performances using either of the moving horizon displays. The pursuit moving airplane configuration exhibited a two-to-one error reduction compared with the compensatory moving airplane display. The ratio of control reversals for the

conventional moving horizon display with an aircraft-stabilized steering dot and the space-stabilized pursuit moving airplane display was 18:1. The authors expressed a reservation as to the extrapolation of these simulator results to actual flight situations.[1]

Frequency Separation Principle

In the studies previously cited, with the exceptions of those by Nygaard and Roscoe (1953) and Bauerschmidt and Roscoe (1960), the alternatives of a moving outside world with a fixed symbol representing the aircraft and an aircraft moving against a stationary outside world have been considered as mutually exclusive arrangements. A third alternative is that of having both the aircraft symbol and the symbol or symbols representing the outside world move, as in the Bauerschmidt-Roscoe display in which some movement relationships were inside-out while others were outside-in. Furthermore, it will be shown that display coordinates may be shifted as a function of time.

It was found in the Gardner and Lacey study (1954) that when the pilot's task required sudden control movements, as in recovering from unusual attitudes and flying discrete tracking tasks, the results were quite different from those obtained when the pilot's task was to hold the aircraft straight and level. In the first case, the moving aircraft type of display was found to be superior; in the second case, performance on the two displays was found not to be significantly different. These findings suggest that a critical consideration is the relative speed of movement of the display indications: when high frequency (suddenly changing or rapidly alternating) information is displayed, the moving element must respond in the expected direction; when low frequency information is displayed, the element's direction of movement apparently is not as crucial.

[1] The Air Force colonels on the Development Engineering Inspection Board for the North American F-108 long-range interceptor were less reserved. Having served as pre-test experimental subjects in the Hughes simulator, their last official act as the F-108 mockup board was a unanimous decision to adopt the pursuit moving airplane steering display. Approximately one week later, in September 1959, the F-108 program was cancelled.

The results of a study by Chernikoff, Birmingham, and Taylor (1955) also indicate that the optimum display configuration might be different in different situations. Pursuit tracking might be preferred for high frequency control; however, compensatory tracking might be sufficient for low frequency control.

These observations led to the notion of using frequency separation as a principle in the design of displays. The best known example of a frequency separated display was introduced by Fogel (1959). Fogel's primary aim in the formulation of what he called a kinalog display (a contraction of kinesthetic analog) was to make visually displayed attitude information more nearly compatible with the information a pilot receives through his kinesthetic and vestibular senses.

Fogel recognized that the proprioceptors sense only accelerations and convey no direct information concerning rates or positions. Since accelerations in an aircraft, particularly the angular accelerations associated with changes in attitude, are typically transient in nature, Fogel reasoned that visual and vestibular compatibility requires only that the initial motion of a display indication from any steady state be in the same direction as the angular acceleration. Thereafter, the direction of display motion may gradually be reversed without conflicting with vestibular and kinesthetic cues. For example, if the pilot moves the control stick to the right to initiate a right turn, the aircraft symbol should immediately rotate clockwise to coincide with the direction of angular acceleration. As the aircraft establishes its right turn and the angular acceleration is replaced by linear acceleration normal to the aircraft's wings, both the horizon line on the display and the aircraft symbol gradually rotate counter-clockwise so that in a steady state turn the aircraft's angle of bank is displayed by the tilt of the horizon bar, as in a conventional presentation.

Generalization of Fogel's basic notion leads to the principle of frequency separation in which high frequency (rapidly changing) information, such as roll and pitch rates, angular accelerations, and control inputs are presented in the

moving aircraft fashion; and the low frequency (slowly changing) information, such as attitude and heading, continue to be presented in the conventional moving world manner.

If such a display configuration were found to be advantageous in presenting flight information, many possibilities would be open to display designers. One of the more obvious of these is that the pilot's flight tasks could be presented in a hierarchical manner (Carel, 1965; Roscoe, 1968). That is to say, in a situation in which rapid or sudden control inputs are necessary, such as in air-to-air attacks, the pilot could respond to higher order, or so-called inner-loop, dynamic indications with compatible control-display motion relationships. Lower-order or outer-loop dynamic variables, such as aircraft position which is neither immediately nor evidently related to control movements, would be presented in the conventional manner. Although the principle of hierarchical frequency separation intuitively has many possibilities, it has never been systematically investigated in an experimental program.

Despite the fact that the frequency separation principle has not been the subject of systematic experimental study, it has found several applications in aircraft cockpits without explicit recognition. The widely used Air Force ID-249, shown in Figure 3, is a frequency separated display in which the aircraft's slowly changing displacement from selected course is presented inside-out, while the aircraft's more rapidly changing heading relative to the selected course is presented outside-in. The Lear LIFE display system shown in Figure 4, which accompanied the L-102 autopilot and was adopted by a few local service airlines flying the Fairchild F-27, presented aircraft attitude outside-in and aircraft heading inside-out in a manner such that the display's peripheral bank index could be aligned with the desired heading index in a pursuit tracking fashion. The display employed in the Butler VAC area navigation system, shown in Figure 5, is frequency separated in the same manner as the ID-249.

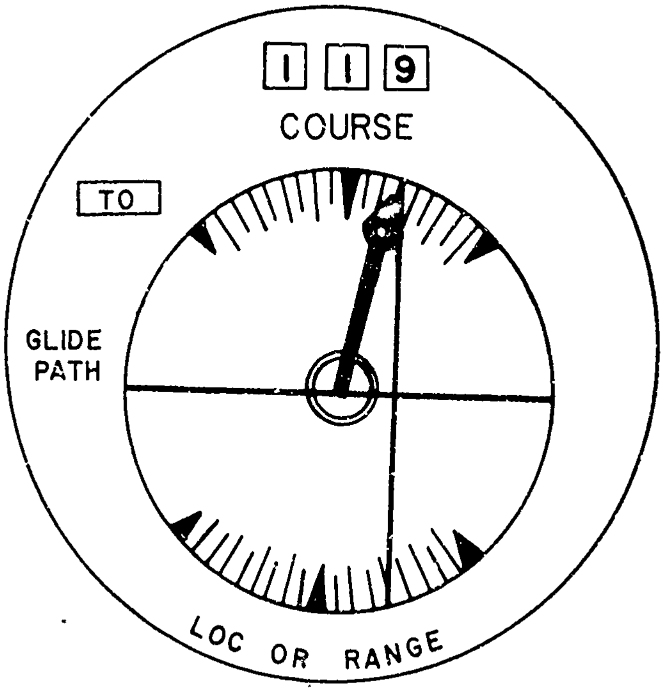

FIGURE 3. ID-249 course deviation and relative heading indicator.

Angular course deviation is represented in an inside-out manner by the vertical needle. Heading relative to selected course is represented in an outside-in manner by the relative heading pointer. The relation between the two graphically presents desired course interception angle.

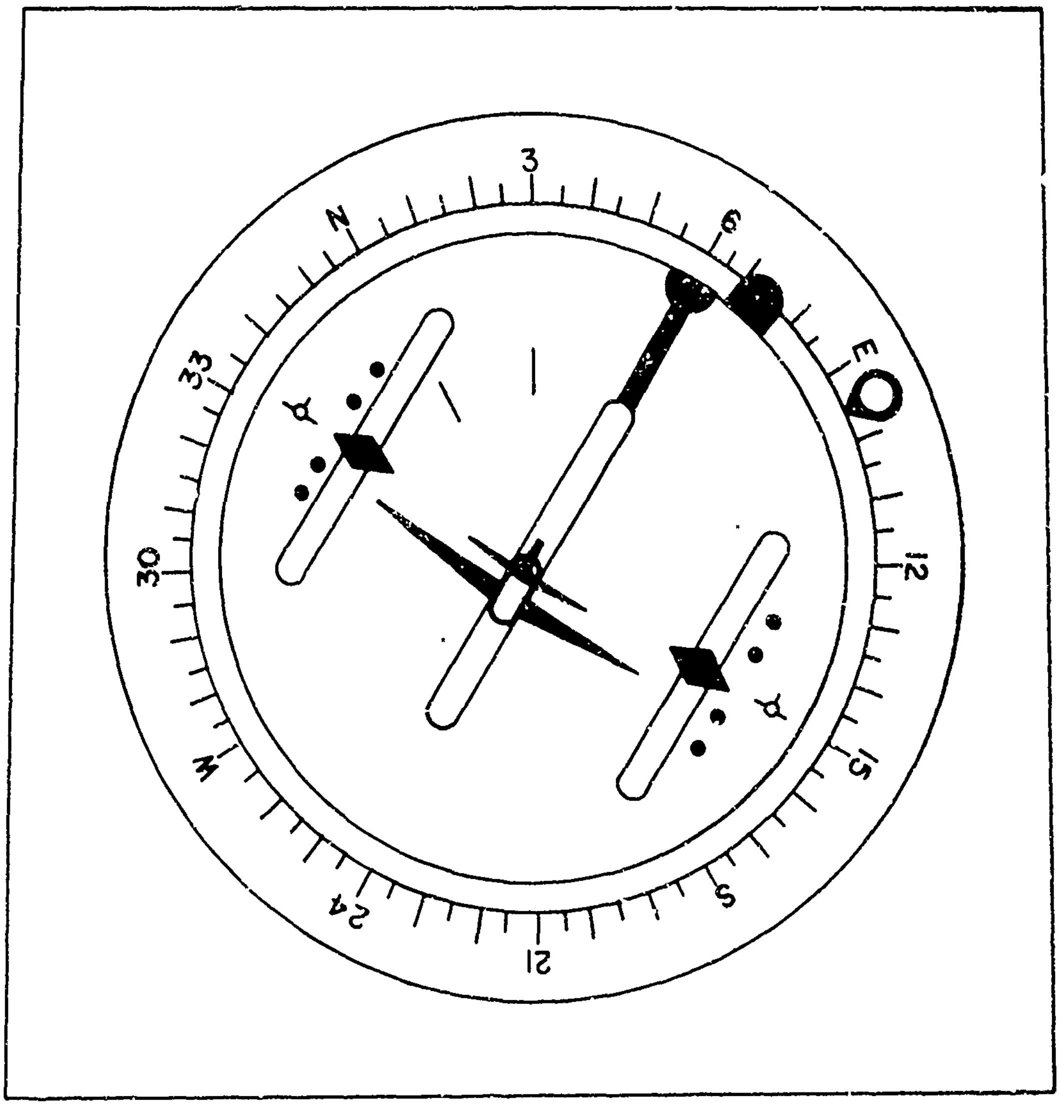

FIGURE 4. Lear LIFE (Lear Integrated Flight Equipment) flight director display.

Actual heading, command heading, command bank and glide slope deviation are all presented in an inside-out manner. Actual pitch and bank are presented in an outside-in manner. Relationships between actual bank and command bank and between pitch and glide slope deviation graphically present the appropriate capture of desired course and vertical flight path.

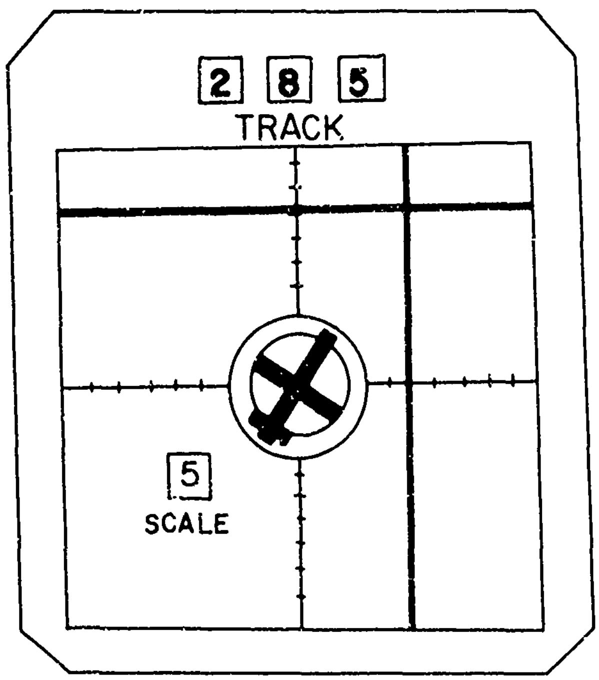

FIGURE 5. Butler SPI (Symbolic Pictorial Indicator).

Linear displacement from desired course, as depicted by the vertical needle, and linear distance to way-point, as depicted by the horizontal needle, are inside-out presentations. Heading relative to selected track (or course) is presented in the outside-in manner. The intersection of the needles relative to the airplane symbol presents a plan view of the horizontal flight geometry.

RESEARCH PROBLEMS

Experience Level

Flight experience on any particular display configuration can have a large effect on the results of a display evaluation study. Some of the studies cited in the previous section (Browne, 1952; Gardner, 1954; Gardner and Lacey, 1954) found different results when experienced pilots, as opposed to novice pilots or non-pilots, were used.

One of the main considerations when evaluating an attitude display configuration is the ease with which a non-pilot can learn to use a particular frame of reference. Not only will this original learning occur more rapidly on a superior display, but also the terminal level of performance on such a display will be higher. With respect to the motion relationships on an attitude indicator, what the non-pilot considers as the expected movement of a display symbol, resulting from a corresponding movement of the pilot's own aircraft, will have a large effect on how quickly he learns to use that display.

The pilot population typically overlearns the use of any conventional display configuration. Therefore, the ease with which a pilot already skilled in the use of a display employing one frame of reference can transition to a new display using a different frame of reference is also important. Although a new display may prove to be substantially superior to an old configuration for a non-pilot subject sample, the effect of habit interference due to extensive experience with the old configuration may outweigh this advantage for an actual flight system. One of the most revealing studies, previously cited, on the question of the transition of experienced pilots to a new display was that done by Casperson of Dunlap and Associates (1955). He found that even ex-military pilots, once highly trained in the use of the conventional moving horizon display, adapted to the moving aircraft display more easily than they re-adapted to the conventional display.

Of particular importance is the effect of stress on a pilot's ability to perform on a new configuration. Although a pilot has seemingly made the transition to a new display configuration with little trouble, in a stressful situation he may revert to former, and now inappropriate, control responses. The contention may be made that a display which utilizes motion relationships compatible with the pilot's response tendencies will offer less chance of the occurence of such a reversal for all levels of pilot experience.

Research Environment

The experimental environment in which a flight display evaluation is conducted must be considered when an attempt is made to extrapolate the findings to real life situations. As is the case in any experimental program, a trade-off must be made among realism, experimental simplicity, and cost. Experimental evaluations of attitude indicators have ranged from laboratory studies which had little realism, but which were relatively easy to conduct because of their simplicity, to actual in-the-air flight experiments costing relatively large sums of money. To date no experimental program of adequate scope has been conducted in a realistic flight environment involving operationally meaningful tasks to provide complete and conclusive answers to basic questions concerning display motion relationships.

One of the most unrealistic studies cited was that of Gardner (1954). This was a laboratory experiment in which the experimenter set the attitude presentation from the back of the display, and the subject verbally announced the control movement necessary to correct the situation. This type of study has the supposed advantage that such variables as control dynamics and fatigue do not enter in as confounding factors. Yet, the results cannot justifiably be extrapolated to the dynamic real-life flight situation.

Most of the studies cited used aircraft simulators in their experiments. Some of the studies used motionless simulators which afford the realism of the cockpit environment but are still suspect in that no kinesthetic or vestibular cues are present.

A study in which these cues were found to have an effect on relative performances while using moving horizon and moving aircraft displays was that of Matheny, Dougherty, and Willis (1963). Studies conducted in moving-based simulators have the advantage of providing certain kinesthetic and vestibular cues; however, these cues are usually limited and never precisely correct. Even with the advantages of motion in a simulator, Douvillier, et al. (1960) found that the results of moving-based simulator studies are still suspect.

It appears that in the case of questions concerning dynamic control-display motion relationships, the ultimate research environment for the purposes of extrapolating to actual flight situations is the aircraft itself in flight. Along with the element of realism comes the difficult problem of experimental control. The experimental design and procedures used in flight experiments must be sufficiently sophisticated to determine or balance the effects of extraneous variables to the largest degree possible.

Pilot's Confidence in the Display

A particularly important aspect of the research environment is the confidence the experimenter manages to instill in the subject. For example, vertigo may result from a contradiction between the information the pilot receives through his proprioceptive senses and through his visual sense, particularly if the pilot has reason to question his visual frame of reference. The real problem in flight arises when the aircraft accelerates about its roll axis at a level below the pilot's vestibular and kinesthetic thresholds. If the pilot is scanning other instruments during this time, when he shifts his attention back to the attitude indicator, he will find the display portraying an unexpected attitude. There will then be a conflict between the pilot's proprioceptive senses, which tell him that he is flying straight and level, and his visual sense, which tells him that he is in a banked attitude. The pilot might then initiate a sharp control movement to correct the undesired attitude shown on the display. This control movement would cause a suprathreshold angular acceleration from what his proprioceptive senses have been

representing as a wings-level condition, thus giving the sensation of rotating for the first time. His conflict and confusion obviously are compounded, for one sense tells him positively that he is correcting an undesirable situation, and the other sense tells him positively that he is moving into one.

Whether the pilot believes his display or his proprioceptive sensations, to a large degree, depends on the pilot's confidence in the display itself. A study by Johnson and Williams (1949) investigated a subject's obedience to rotation-indicating displays as a function of his confidence in the display. Four experimental conditions defined in terms of the type of visual display presented were chosen to be tested separately under each of two levels of confidence. The subject entered a small cubicle mounted on a turntable in a large laboratory room. He viewed whatever was presented to him through a window as the turntable was accelerated in either direction. The first experimental condition gave the subject a restricted view of the walls and furniture of the laboratory in which the experiment was being conducted. The second experimental condition also gave a restricted view of the laboratory, but a system of mirrors bilaterally reversed the visually apparent rotation of the cubicle, thereby giving contradictory visual and vestibular cues. The third experimental condition presented a painted panoramic display simulating the earth, sky, and horizon as viewed from the air. The display was quite realistic, but it could not be mistaken for the actual surroundings. Its apparent movement was correctly oriented. In the fourth experimental condition, the display was the same as in the third except that its apparent movement was in the wrong direction for the actual rotation, again giving the subject conflicting visual and vestibular cues as accomplished by the mirrors in the second condition.

One group (low confidence) was shown the experimental apparatus and therefore knew that the experimenter could deceive them. Another group (high confidence) was not shown the apparatus and, therefore, had no reason to doubt the visual information presented. In addition, the high confidence group was

instructed in such a way as to make them believe that the perception of angular acceleration was being tested rather than the perception of the direction of motion.

The responses of the low confidence group were inconsistent and indecisive compared with those of the high confidence group who responded consistently and without evident confusion to the visual cues presented, whether correct or incorrect. The subjects who had little or no reason to doubt the information presented on the display payed much less attention to their proprioceptive senses, whereas the subjects who were expecting to be misinformed by the display payed more attention to their proprioceptive senses with a consequent deterioration in their performances.

These results demonstrate that the pilot's confidence in a display, especially when the situation exists in which there is a potential conflict between his senses, has a large effect on his performance. Ideally, a visual display should give the pilot information that agrees with his proprioceptive senses and still portrays the aircraft's situation correctly. Such a display would reduce the conflict between the senses which results in vertigo. It was precisely this conflict that Fogel hoped to resolve with his frequency-separated kinalog display.

Tasks

The tasks associated with experiments evaluating flight displays must also be considered when determining the extent to which the results can be generalized. There are three primary categories of tasks: ground referenced, air-mass referenced, and time referenced.

In the first catagory, ground referenced tasks, the pilot must maintain orientation with respect to the earth beneath him at all times. Some examples of ground referenced tasks are instrument approaches to landing, turns around a point, air-to-surface weapon delivery, and navigation by pilotage.

The second catagory, air-mass referenced tasks, encompasses such conditions as air-to-air attack missions. Theoretically, in such a situation, the pilot can divorce himself completely from all orientation with respect to position or objects

on the ground. The pilot's sole task is to pursue a target which is subject to all of the physical forces (particularly air-mass movement) that his own vehicle is subject to.

The third category, which is somewhat difficult to separate from a ground referenced task yet is basically different, is that of time referenced tasks. An example of a time referenced task is a vertical-S maneuver. In this maneuver, the task is to make a 180-degree turn and simultaneously climb 500 feet in one minute, then make a 180-degree turn in the opposite direction and descend 500 feet in one minute. This task is time referenced in that it is executed with respect only to time and is not dependent on any particular ground or air-mass reference. It can be initiated from any heading and altitude. As is immediately evident, a single task can involve a combination of two or even all three of these catagories.

In any particular situation, the tasks a pilot must perform, either sequentially or simultaneously, to fly the aircraft are generally characterized by more than one of the previously mentioned catagories. Thus, the possibility arises of different display motion relationships being used in conjunction with different tasks.

Performance Measures

The measures which are used to judge the pilot's relative performance on different display configurations must be considered when an attempt is made to generalize the results to other situations. These performance measures must be relevant to both the experimental and real world situations. The measures should be valid in that they enable the experimenter to predict the pilot's performance in actual flight operations from the results derived in the experimental situation.

The tasks themselves often dictate the particular performance measures used in the evaluation of a display. For instance, in air-to-air-attack, the angle-to-turn-through at firing is a performance measure directly related to the system's operational effectiveness. In another situation, this measure might be less appropriate or even irrelevant. The scores most commonly used in a tracking

task are time-on-target, root-mean-squared error, and average absolute error. These scores may be applied to a variety of measures, such as lateral displacement from course, angle-to-turn-through to capture or hold course, bank-angle or turn-rate error, angular-acceleration error, or even control-position error.

RESEARCH REQUIREMENTS

The Problem Is Real

The incidents reported by Fitts and Jones are but the visible portions of an iceberg. Domestic and military accident reports, scope camera films from the Air Defense Command, and the everyday experiences of students and instructors of instrument flight allow a more comprehensive estimate of the incidence of both momentary and persistent control reversals associated with the misinterpretation of conventional attitude and steering displays. The frequency is higher than is generally recognized, and the consequences include increased pilot training requirements, reduced operational effectiveness, and losses in lives and equipment.

The Evidence Is Flimsy

Experimental findings reported range from suspect to inconclusive. The best experiments from the standpoint of scientific rigor have been conducted in fixed-base simulators, the applicability of which is suspect in questions involving physical motion. There has been no conclusive flight experiment dealing directly with the basic issues discussed.

The Questions Must Be Answered in Flight

It is evident that rigorous and comprehensive experimental research is required as a basis for any rational change from current motion relationships in aircraft instrument displays. It is essential that certain critical experiments be conducted in flight to eliminate the possibility of drawing spurious conclusions from a simulated flight environment. Both the speed of learning by relatively inexperienced pilots and the ease of transition of highly experienced and

currently proficient pilots must be measured. Flight tasks must be operationally realistic and representatively difficult and stressful. Performance measures must be relevant to successful real-life flight operations. Ultimately these crucial flight experiments should be repeated in both fixed-base and moving-base simulators to evaluate the suspect but as yet undetermined validity of experimental results from static and dynamic simulated flight environments.

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Aviation Research Laboratory Institute of Aviation University of Illinois	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

What Moves, the Airplane or the World?

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (First name, middle initial, last name)

Johnson, Steven L. and Roscoe, Stanley N.

6. REPORT DATE June 1970	7a. TOTAL NO. OF PAGES 47	7b. NO. OF REFS 36

8a. CONTRACT OR GRANT NO. N 00014-67-A-0305-0014	9a. ORIGINATOR'S REPORT NUMBER(S) ONR-70-1
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research

13. ABSTRACT

Display motion relationships for attitude and steering indicators have always been controversial issues in flight display design. The questions involve whether the pilot thinks the aircraft is moving relative to the outside world or the outside world is moving relative to the airplane. The pertinent information, obtained through both experience and formal experimentation, is reviewed. An alternative to the standard forms of attitude presentation employs the frequency separation principle. The problems considered when doing experimental investigations on flight displays are subject pools, research environments, flight tasks, and performance measures. Research requirements necessary to solve the longstanding questions on display motion relationships are presented.

DD FORM 1 NOV 65 1473

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Flight Displays						
Cockpit Instrumentation						
Symbology						
Human Factors						
Attitude Displays						
Flight Directors						
Attack Steering						
Pursuit Displays						
Compensatory Displays						